# EFFECTIVENESS OF THE USE OF TRAVELING MAGNETIC FIELD REVERSALS IN ALLOY STIRRING

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**Abstract** : We have used stirring of liquid metal impacted by the travelling magnetic field. As the travelling magnetic field direction changes, the flow is restructured in the bath filled with metal. The flow restructuring is of interest in terms of stirring process intensification. The paper presents the experimental and numeric research into the influence of the flow restructuring on passive impurity stirring process.

## 1. Introduction

Usually, stirring means a process during which the degree of homogenization increases. Stirring is widely used in industry to intensify preparation of mixtures (alloys in metallurgy). The process intensification enables saving time, energy, resources, and improving the finished product quality and reducing the reject rate.

The impurity stirring research can not be wholly reduced to the velocity field study problem. However, if there is some convection, it is evident that degeneracy of spatial inhomogeneity of scalar field is mainly determine by the velocity field. Herewith the flow structure impacts stirring as much as the velocity amplitude. The paper is concerned with the study of the effect of passive impurity stirring intensity increase during the flow restructuring. The flow restructuring means the change of the flow structure occurring in several seconds.

Application of the external rotating magnetic field reversal mode for impact on liquid metal was suggested in [1]. We used this method as applied to the travelling magnetic field to enable the flow restructuring. In [2] we have already generally studied the formation of stirring flow in molten metal by means of the travelling magnetic field. It was noticed that the impurity homogenization rate is slowed upon formation of “stationary” flow. Herewith, as the numerical study showed, the process can be intensified using the travelling magnetic field direction change (reversing).

The electromagnetic forces in the melt in the mixer furnace bath are determined by amplitude and frequency of the electromagnetic field at the bath wall which is generated by the TMF induction coil current. So, the medium properties, cavity shape, amplitude and frequency of the current wholly determine the stirring process. It can be demonstrated how any change of these parameters influences the flow on qualitative estimate level. However, any estimate of the influence of the travelling magnetic field reversal (TMFR) on the flow structure is a more complicated problem.

To estimate any influence of TMFR on the impurity stirring it is necessary to understand the processes occurring during reversing, especially those in the time interval from the travelling magnetic field direction change till achievement of a quasistationary mode by the flow. To that end some experimental measurements of the reversal mode velocity were performed, as well as numerical simulation of the passive impurity transfer.

## 2. Experimental details

The experiment was designed with the goal to study the molten metal flow in the reversal mode. The experimental setup consisted of: a bath, a travelling magnetic field induction coil, a power supply, a three-phase transformer. The velocity was measured using an ultrasonic Doppler velocimeter (UDV, model DOP 2000, Signal Processing SA, Lausanne). The bath capacity was 8 L. The bath was manufactured of textolite, the front wall being made of organic glass. The working metal was gallium alloy (Ga 87,5%, Sn 10,5%, Zn 2%), in liquid phase at 170C or higher temperature. The liquid layer height was 9.5 cm. The vertical section of the bath is rectangular trapezoid with 9.5 cm height and 18 and 24 cm bases.

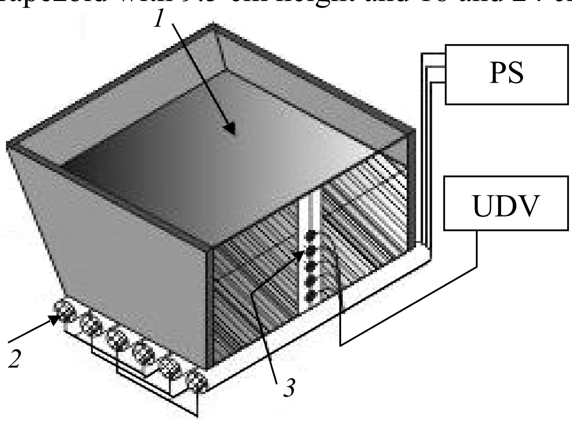


Figure 1: Schematic of the experimental setup. 1. – liquid metal; 2 – magnetic field inductor; 3 – UDV probes; UDV – ultrasonic Doppler velocimeter; PS – power supply.

A travelling magnetic field induction coil located under the bath bottom was used for formation of the flow in the melt. The induction coil created the volume force in the liquid metal directed along the bath bottom parallel to its side walls. The main forces were focused in the skin layer of the electromagnetic field near the bath bottom.

The metal movement velocity was measured using ultrasonic Doppler anemometer (UDV, model DOP 2000, Signal Processing SA, Lausanne) equipped with 4 MHz sensors (TR0410RS diameter 10 mm, Signal Processing SA, Lausanne), operating in multiplexer mode. Five sensors UDV (1-5 channel, sensor numbering is from below upwards, see Fig. 1.) were located on the front ultrasonic-transparent plexiglass wall of the setup on a special, horizontally sliding rail. The center-to-center distance between the neighbouring sensors is 1.5 cm.

## 3. Numerical simulation

Despite physical simulation is widely used in studying of multiphase media, it is often difficult to observe the conditions of similarity and to conduct experimental measurements which makes it necessary to prefer the numerical simulation when studying the impurity transfer.

There are many approaches and models for the numerical study of multiphase flow behaviour which were embodied in several computation techniques which can generally be classified as one of two Euler or Lagrange methods. For purely Eurlerian methods, a common approach is to make the “one-fluid” assumption in which a number of different fluids are modeled as a single fluid with rapidly varying material properties[3]

As a result, the system to be solved actually looks as follows:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \nu\Delta\mathbf{V} + \mathbf{g} + \frac{\mathbf{f}}{\rho},$$

$$\mathrm{div}\mathbf{V} = 0 ,$$

$$\frac{\partial C}{\partial t} + (\mathbf{V}\nabla)\mathrm{C} = \nabla \cdot (D\nabla C) ,$$

We consider the electrically conducting fluid, so the right hand side of the equation includes the electrodynamic body force induced by the travelling magnetic field. The approximate solution for the force in a flat layer of a conducting material induced under the influence of the travelling magnetic field in Fourier space was obtained in [4]:

$$f_x = \frac{9{I_0}^2\mu_0}{\pi^2 {R_0}^3 e^2 \rho} \frac{ch(2ky)}{ch(2kh)} e^{2i(\omega t - \frac{x}{\lambda})}$$

This system was solved using library interFoam CFD model (included into OpenFOAM). The common property of the computation techniques used in OpenFOAM is the use of a 3D non-structured finite-volume grid, in addition, all models enable vectorizing the computation process.

To estimate the stirring efficiency, we have introduced the stirring efficiency parameter which is just the mean square deviation of concentration in the whole volume. This parameter was normed for a unit to make it convenient.

There are several approaches to stirring estimate. However, the researches use mainly some methods for their particular problem and conditions, for example: achievement of 95% homogenization of scalar field in the volume being mixed [5]. We use the efficient stirring time parameter in out approach. It is the time in which the initial stirring efficiency coefficient decreases by factor of 10.

## 4. Results

At a first approximation, the hydrodynamics of the process being studied without any use of reversal can be assumed as follows: At first, liquid is resting, once the inductor is switched on, the electromagnetic force accelerates the liquid and in some time the quasistationary flow is set in the liquid. In the experimentally measured mode the flow is one big stable whirl with small unstable whirls near the walls and corners of the bath. The maximum intensity of the flow is near the bottom and surface. The electromagnetic energy is used for the formation of a big whirl, its spin-up and dissipation of the energy on the walls.

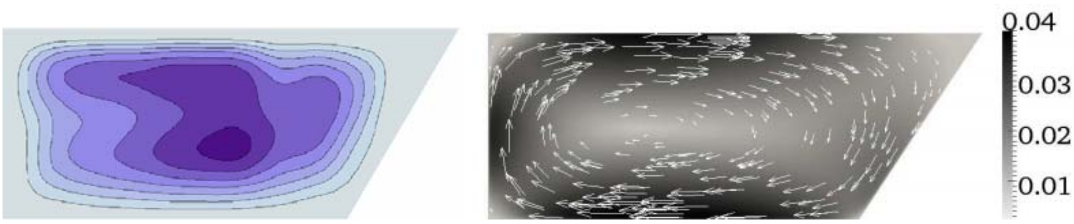


Figure 2:The flow pattern reconstructed using the experimental measurements (left) and the numerical computation results (right).

The results of computations and experimental measurements of the velocity profiles along $x$ axis for 15 Hz frequency values in 200 A induction coil are shown in Fig 3.

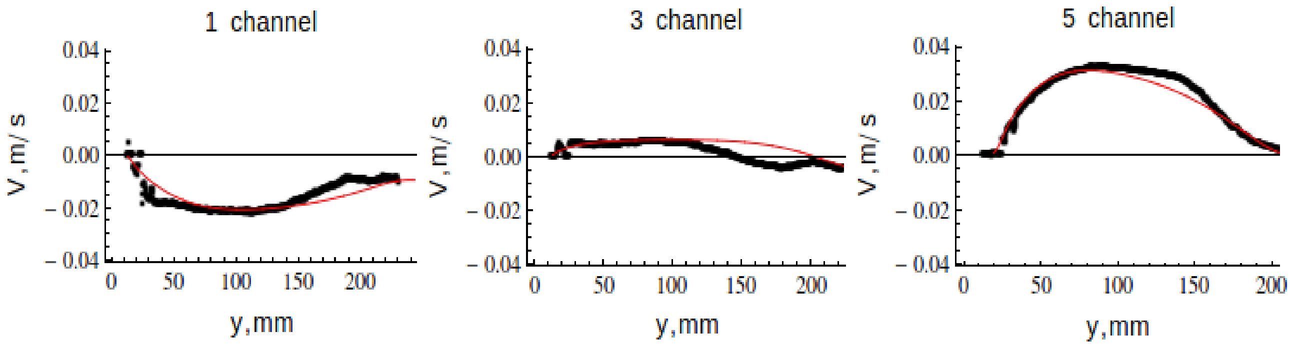


Figure 3: Average velocity profiles (red line) obtained from computations vs experimentally measured profiles (black line).

Fig. 3 illustrates that the numerical simulation results match with the experimental data well.

As the numerical simulation results show, the impurity transfer dynamics in its turn can be illustrated as follows. At first (several seconds after the beginning) the intense dissolution of the impurity occurs. Some temporary whirls stirring the impurity occur. At the same time, the stable flow (a large-scale whirl) is formed. Once the stable whirl is formed and absorbs the impurity, the impurity in the center of the whirl is transferred as a whole due to possible suppression of any turbulent fluctuations, and its rearrangement slows down resulting in the decrease of the rate of the impurity "dissolution". At the same time any turbulence facilitates the impurity breakaway and carrying away to the hydrodynamic swirl due to which stirring continues "slowly and surely".

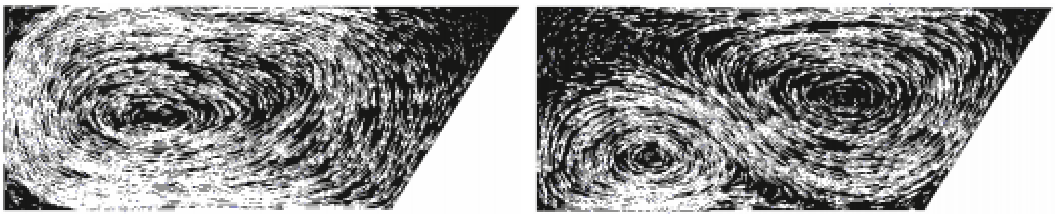

Figure 4: An example of the numeric calculation for 0.01 Hz reversal frequency.

When the reversal is used, the electromagnetic force is controlled in such a way that during the first half of the time interval the electromagnetic force acts in one direction, and during the second half of the time interval it acts in the opposite direction.

Some experiments were conducted to study the reversal at different frequencies. The general conclusion of them was: the flow structure is only determined by the reversal frequency in a particular frequency range. At low frequencies, when the force action in a respective direction is dozens of seconds, the liquid is highly responsive to the force action, and the structure of the flow itself is one or two interacting whirls.

At higher frequencies, when the reversal halfcycle is about on second, the liquid behavior is less predictable. Due to inertia of the liquid, when the low layers are decelerated and turn in the opposite direction, the upper layers still continue to move in the previous direction. So, as the reversal frequency increases, the whole flow is decelerated, becomes more complicated and unstable. The high-frequency reversal prevents the flow from the full development, and the velocity intensity is lower in this case than in the case where it is absent. Thus, the low-frequency reversal, when the stationary mode and transfer mode co-exist, is of interest.

The experimental research into this mode revealed an interesting peculiarity. During the transitional flow some zones are formed in the liquid where the velocity exceeds one under the permanent stirring. Once the main flow is formed, the flow velocity is slowed down. It can be explained by the fact that less energy is consumed for the stationary structure maintenance than for the flow restructuring. During the restructuring a boosted turbulization occurs locally causing the increase of the kinetic energy dissipation and intensifying of the diffusion processes.

The velocity profile formation process during reversal can be divided into several stages:

1. There is a developed flow.
2. After the reversal "the feeding" of this flow is suspended but still functions. At the same time the energy for formation of the other flow is exhausted.
3. At the third stage a new structure is formed, the areas from the new and old structures existing simultaneously. The lack of energy for maintenance of the existing mode results in unstabilities which cause destabilization of the system and its destruction. Because the new flow embraces only some part of the whole volume, the velocity in such a flow exceeds the stationary flow velocity locally.
4. The new structure becomes prevailing, and any rudiments of the old structure disappear.
5. Spin-up of the new structure.

## 5. Conclusion

This paper investigated any influence of the flow restructuring using the travelling magnetic field reversal on the impurity stirring in the molten metal experimentally and numerically. The impurity homogenization in the flow under investigation proceeds influenced by three inter-related flows: A large-scale transfer of the impurity by big whirls, stirring by means of the full-scale medium movement up to turbulence scale, and stirring by means of the molecular diffusion.

The research showed that the flow restructuring by reversing makes the flow more complex and divides the big and stable whirls into several ones. Thus the use of the reversal makes the energy distribution more uniform over the space. In addition, the reversal enables to locally achieve the short-term velocities exceeding those in a single-direction flow, thus making regions with the increased turbulization in a volume which also facilitate the stirring intensification.

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## 4. References

[1] Eckert, S. et al.: Efficient melt stirring using pulse sequences of a rotating magnetic field: Part 1. Flow field in a liquid metal column. Metallurgical and Materials Transactions B, 6 (2007) 977–988.

[2] Oborin, P.A.; Khripchenko S.Y. Study of liquid metal flow and passive impurity transport driven by a traveling magnetic field in a rectangular cavity Computational continuum mechanics. 2 (2013) 207-213.

[3] Morgan, G: Application of the interFoam VoF code to coastal wave/structure interaction. PhD Thesis (2012).

[4] Ostroumov, G.: Physical and mathematical foundations of the magnetic stirring melts. Metallurgizdat, Moscow, 1960 (in Russ.).

[5] Roy; S.; Acharya, S; Scalar mixing in a turbulent stirred tank with pitched blade turbine: Role of impeller speed perturbation. J Chemical Engineering Research and Design. 7 (2012) 884-898.